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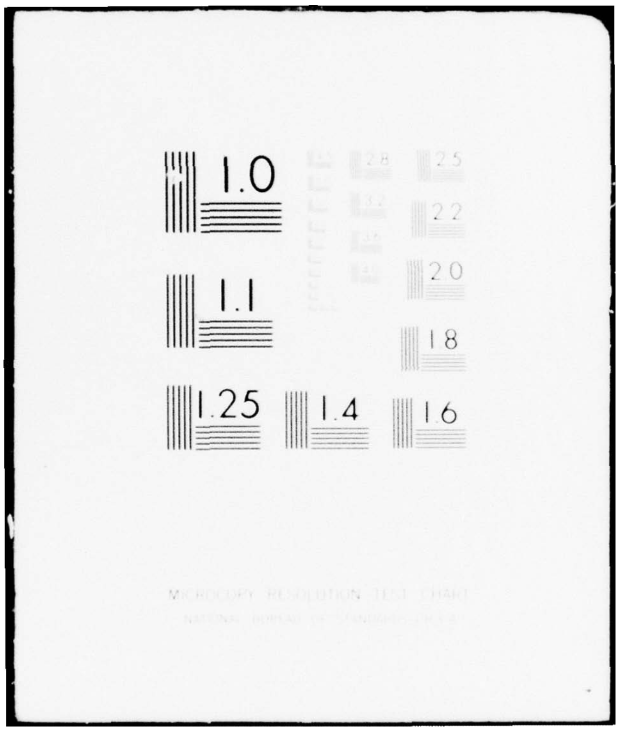
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An Introduction to V/STOL Technology Affecting the Pilot's Role

by
Robert F. Ringland
Systems Technology, Incorporated
for the
Systems Development Department

DECEMBER 1977

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Naval Weapons Center
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Naval Weapons Center

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FOREWORD

This task was conducted to provide background material on V/STOL technology for those interested in the human factors aspects of future V/STOL aircraft development. The task was requested and technically monitored by Ronald A. Erickson, with the support of Paul Linton, Human Factors Engineering Division, Naval Air Development Center.

The task was conducted as a follow-on to a problem definition study of past V/STOL development programs (see NWC TP 5941). It was conducted by Systems Technology, Inc. under Navy contract N60530-77-M-H604. Irving L. Ashkenas, Samuel J. Craig, Richard Walchli, and Sqn. Ldr. John Lloyd assisted in reviewing the report for technical accuracy.

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2 November 1977

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(U) *An Introduction to V/STOL Technology Affecting the Pilot's Role*, by Robert F. Ringland, Systems Technology, Incorporated. China Lake, Calif., Naval Weapons Center, December 1977. 42 pp. (NWC TP 5996, publication UNCLASSIFIED.)

(U) This report provides introductory material on the aerodynamics, propulsion, and flight control for V/STOL aircraft. Certain basic aspects of V/STOL technology and hardware are outlined, and deficiencies in past V/STOL aircraft which adversely impact the pilot's performance are discussed. The report is intended to provide background material on the human factors aspects of future V/STOL aircraft development.

CONTENTS

INTRODUCTION

A V/STOL aircraft is one capable of takeoff and landing in the vertical direction or with a short ground roll as compared with conventional aircraft. The technology which makes these unconventional modes of flight possible for a practical aircraft is a significant departure from conventional aircraft design in the areas of aerodynamics, propulsion, and flight control.

The piloting tasks in the unconventional flight regime are likewise different. This is primarily because of differences in task goals and differences in the V/STOL aircraft's responses to the pilot's controls. Additional differences arise out of the nature of the V/STOL's lift/propulsion system — certain kinds of aircraft motion instabilities and unusual sensitivity to aerodynamic disturbances. Both imply additional tasks for the pilot, or functions for automatic flight controls. The result in past V/STOL designs has been excessive workload demands on the pilot in one or more flight phases.[1]

This report provides a brief outline of V/STOL technology which has impact on the pilot's role. It is intended for readers involved in human factors aspects of V/STOL development which in past programs usually have been regarded as peripheral to the aerodynamics, propulsion, and flight control technologies discussed here. It is assumed that the reader has at least a casual acquaintance with conventional aircraft and their aerodynamic principles of operation.

The report begins with a description of the V/STOL aircraft, its key distinguishing features, and its operating principles. The description is expanded in the areas of propulsion and flight controls, then pulled together in an outline of the V/STOLs' motion behavior as realized in past designs. The report concludes with an outline of future trends in V/STOL aircraft design.

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[1] Naval Weapons Center. *Survey of Piloting Factors in Fixed Wing V/STOL Aircraft*, by Robert F. Ringland, Samuel J. Craig, and Warren F. Clement, Systems Technology, Inc. China Lake, Calif., NWC, February 1977. (NWC TP 5941, publication UNCLASSIFIED.)

V/STOL AIRCRAFT

The design of any aircraft, be it a conventional airplane or an unconventional V/STOL, requires the resolution of a number of potentially conflicting requirements in the several interrelated areas of aircraft design. This section explores the nature of V/STOL aircraft by outlining some general requirements and characteristics and presenting a limited number of example aircraft to illustrate key configuration design aspects. These include disk loading, engine failure, conversion methods, and control force generation.

WHY V/STOL?

Because of the requirement for relative motion between the lifting surface (airfoil) and the air in order to generate lift, the conventional airplane must achieve some minimum speed on the ground before it can become airborne. This requires a runway which allows the airplane some distance for accelerating up to the takeoff speed. In landing, the runway is similarly used to allow deceleration from the landing speed to a stop. For launch and recovery on ships where the available distance is considerably shorter, catapults are used to launch the airplane; arresting cables are used to slow it down on recovery (landing). These devices permit much higher rates of acceleration and deceleration than are possible with the airplane alone. Using a conventional aircraft therefore implies the need for a large ground area within which the airplane can land or take off, or a large ship with catapult and arresting gear for airborne operations. Both are expensive, particularly in the military context where there is considerable merit in being a small target rather than a large one.

An aircraft capable of leaving the ground vertically, without a takeoff run, and landing in a similar space requires a much smaller airfield or ship. An aircraft with this capability is termed a VTOL, for Vertical Take-Off and Landing. The definition includes both fixed-wing VTOLs and rotary-wing helicopters. An aircraft capable of leaving the ground at very low forward speeds, thereby not requiring a lengthy distance to accelerate, will allow a similar, although not as great, an advantage. Such an aircraft is termed a STOL, for Short Take-Off and Landing. Here the definition generally excludes helicopters. An aircraft capable of operation in both the VTOL and STOL modes is termed a V/STOL. Either capability is distinct from the conventional airplane which, by analogy to the acronyms above, can be termed a CTOL, for Conventional Take-Off and Landing.

GENERAL CHARACTERISTICS

The V/STOL aircraft is capable of generating lift greater than its weight at zero forward speed. In accordance with the general requirements for all aircraft, it must be safe and easy to fly and economical to operate in its intended mission. It has a means for generating high static thrust in the vertical direction; its thrust-to-weight ratio is greater than one, in contrast to most CTOLs where this ratio is less and sometimes considerably less than one.

After leaving the ground in the VTO mode, the V/STOL must have a means for directing its thrust in the horizontal direction for forward flight. This must be possible in a progressive fashion as the aircraft accelerates from a hover. If the V/STOL has fixed wings (i.e., all V/STOLs except helicopters wherein the "wing" is in continuous rotation with respect to the aircraft), it accelerates to purely wing-borne flight, where it uses the thrust only for propulsion. That portion of its flight between hovering or thrust-supported flight and purely wing-borne flight is termed transition or conversion flight.

Finally, the V/STOL must have a control system permitting the pilot to maintain an equilibrium balance (trim) among the forces and moments acting on the aircraft and to control attitude, path, and speed throughout hovering, transition (conversion), and wing-borne (conventional) flight. Such systems are relatively complex compared to the case for a CTOL because of the wide range in speeds and the relative lack of inherent stability characteristics at low speeds. Conventional control surfaces rely on the relative motion between the aircraft and the air through which the aircraft moves to generate both stabilizing and controlling forces and moments. At zero airspeed, these are absent, and the propulsive lift system must be used to generate some or all of the necessary forces and moments.

V/STOLs lack inherent stability qualities at low speeds, not only because conventional stabilizing surfaces are ineffective, but also because operation of the active lift systems (downward-directed thrust) typically involves destabilizing tendencies. Such tendencies include ground effects, which are the forces and moments acting on the hovering V/STOL which are caused by the interaction of the downward-directed gas flow with the ground. Hot gas ingestion (HGI) is another problem; the engine loses thrust or power because it ingests some of its own exhaust gases. This condition usually takes some time to develop and depends on the prevailing wind and aircraft height above ground. Other attitude disturbances come about through the reaction forces produced by altering the direction of high-velocity air flow as it enters, flows through, and leaves the aircraft. The flow turning forces are sometimes given special names, e.g., intake momentum drag, and will depend in part on the airflow conditions external to the aircraft.

These forces and moments can overpower whatever conventional stabilizing forces are present at low forward speeds. The result is that equilibrium must be restored by the pilot or by automatic devices acting through the V/STOL's flight control system. This is in marked contrast to most CTOLs where greater reliance can be placed on the inherent aerodynamic properties of the aircraft to maintain trim.

EXAMPLE AIRCRAFT

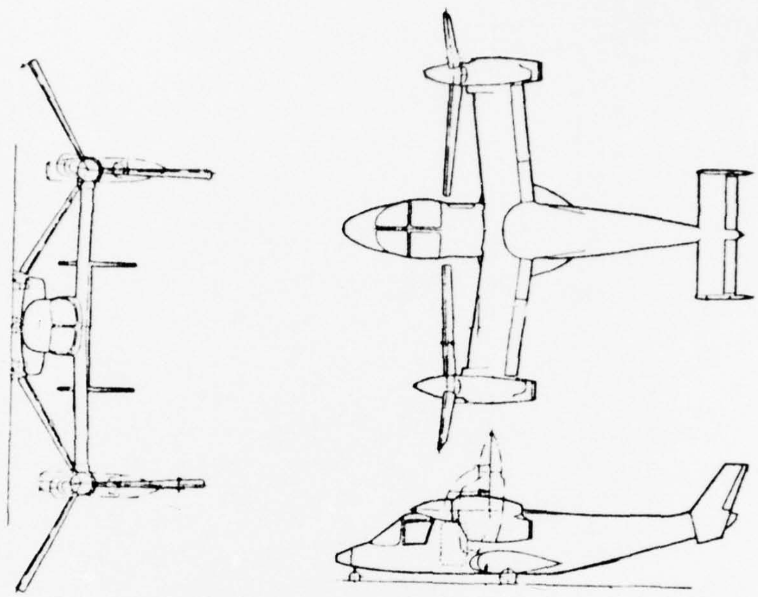
Figure 1 illustrates two V/STOL aircraft which represent extremes in design concept. The first, the XV-15, is a twin-engine, gas-turbine-powered research aircraft recently built for the U.S. Army and the National Aeronautics and Space Administration. As shown by the dotted lines, the engine nacelles at the wing tips rotate in the fore and aft vertical plane to orient the proprotor and resulting thrust force from the horizontal to the vertical direction. The aircraft takes off and lands with the nacelles oriented vertically; in cruising flight the nacelles are oriented horizontally. The term "proprotor" is used to indicate the dual usage of what fundamentally is a helicopter rotor with some degree of compromise in its aerodynamics to suit it for horizontal flight, that is, as a propeller.

The second aircraft, the AV-8A, is a single-engine, fan-jet-powered V/STOL with the engine exhausting through four rotatable nozzles, two on either side of the fuselage under the wings. In the Figure 1b side view, these nozzles are shown as two circles, one just under the leading edge of the wing, the other (partially obscured) somewhat aft of the first. The nozzles rotate to direct the jet exhaust downward for takeoff or landing in the vertical direction; they are directed aft for forward flight.

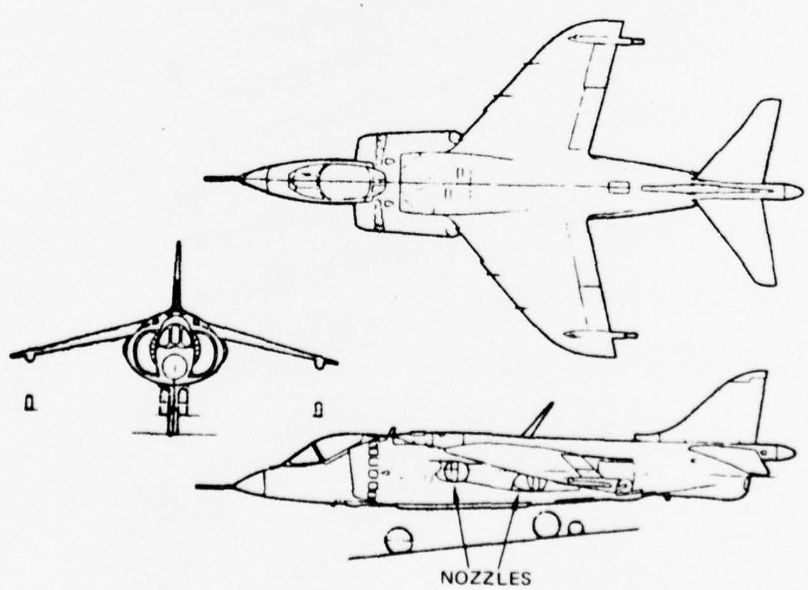
Figure 2 shows four additional V/STOL aircraft having markedly different lift/propulsion concepts. The first is a propeller-driven V/STOL transport prototype. The entire assembly of wing and four engine nacelles rotates to the vertical for vertical takeoff and landing, hence the term "tilt wing." There is a small, vertically oriented propeller at the rear which is used to control the pitch angle of the aircraft in hovering flight.

The next aircraft (Figure 2b) is also propeller driven, only here the propellers are inside short ring-shaped ducts. The ducted propellers all rotate to direct the thrust vertically ("tilt duct" describes the configuration) for takeoff and landing in the vertical direction. This aircraft is powered by four turboshaft engines, drive-shaft-connected to the ducted propellers, and most clearly visible in the top view on the aft wing.

Figure 2c shows another research aircraft, this one using fans for lift in the vertical takeoff and landing mode. In the top view these fans are visible as three circles, one in each wing and the third in the nose.



a) XV-15 TILT ROTOR RESEARCH AIRCRAFT



b) AV-8A HARRIER

FIGURE 1. Extremes in V/STOL Concept.

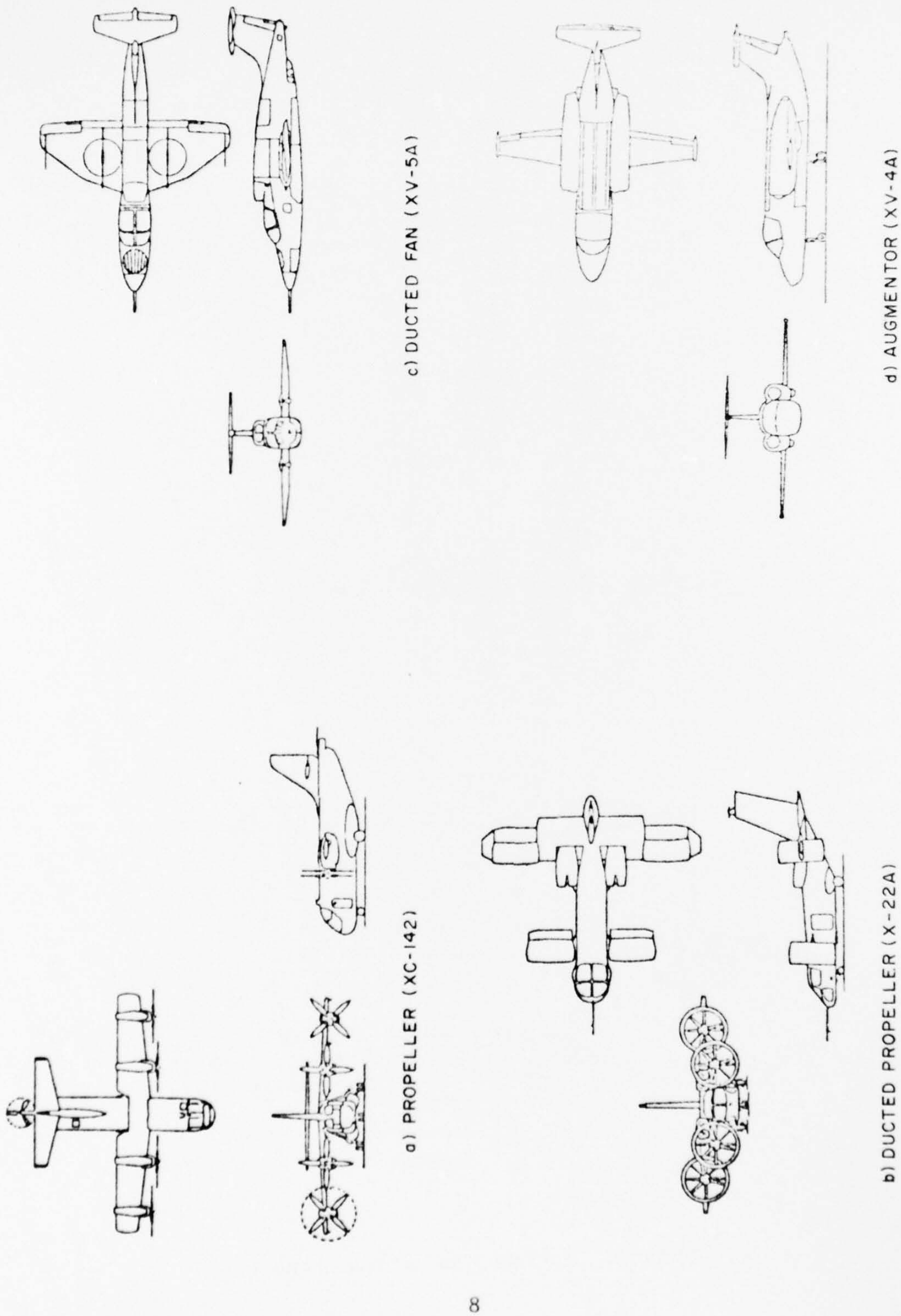


FIGURE 2. Additional V/STOL Aircraft Examples.

The fans are powered by the turbojet engine exhaust gases which are ducted to turbine blades at the tips of each fan. For the fans to operate, semicircular doors above the wing fans and louvers above the nose fan open for the intake of air. The fans exhaust through venetian-blind-like louvers in the wings, clam-shell-like doors at the nose. Manipulation of the fan speed, louvers, and doors controls thrust direction and magnitude. The two engines are located at the fuselage and exhaust to the rear for conventional flight through nozzles visible in the side view. The engines' air intake is just above and behind the cockpit.

The last aircraft, shown in Figure 2d, employs the augmentor principle (see next subsection) for propulsion. The nacelles on either side of the fuselage contain turbojet engines which exhaust through the augmented jet ejector system in the fuselage for vertical flight. Figure 2d shows the doors on the upper and lower surfaces of the fuselage which open up for flight in this mode. For forward flight the turbojet flow is diverted from the ejector system to conventional exhaust ducts.

V/STOL DISK LOADING

To generate the thrust required for vertical takeoff requires that a mass of air or other gas be accelerated to some velocity and expelled downward. The mass times the acceleration of the downward-expelled gases equals the upward force generated on the V/STOL in accordance with Newton's Second Law of Motion. This force can be produced by a large mass of air accelerated to a relatively low downward velocity or a smaller mass accelerated to a higher velocity, the momentum change represented by the accelerated mass of air being the same in either case. A typical example of the former case is the XV-15 Tilt Rotor Aircraft; of the latter case, the Marine Corps' AV-8A Harrier aircraft (Figure 1).

In these examples, which represent low and high disk loading cases, respectively, the downward thrust is regarded as being evenly distributed over the circular area swept out by the helicopter rotor, or by the exhaust nozzle area. More generally, since an exhaust nozzle need not be circular, one can speak of a high exit area loading in the latter example. The important point is that low disk loadings represent relatively low downward air mass velocity, while high disk loadings represent high downward air mass velocity.

Referring to Figure 2, other V/STOL thrusting devices between these extremes include, in the order of increasing disk loading, the following:

1. Propeller — Smaller diameter and higher rpm than the rotor. Blade pitch is controllable. This is usually used in combination with a tiltable wing.

2. Ducted Propeller — An annular duct surrounds a somewhat smaller propeller. This substantially increases the propeller's efficiency and the effective disk loading.

3. Ducted Fan — A smaller duct surrounds a many-bladed fan, the arrangement being optimized for relatively high velocity gas flow. This scheme and the following have similar exit area loading.

4. Augmentor — A high velocity jet exhaust in an axial direction within a larger duct (Figure 3). The primary jet "entrains" additional, secondary gas flow, i.e., pulls in additional air at the front and exhausts it at the rear to "augment" the thrust produced by the jet itself. The ejector elements are usually "staged" so that the secondary airflow becomes the primary flow for yet a larger concentric duct of additionally entrained air. The technique can be particularly effective at low speeds, and the geometry need not be circular.

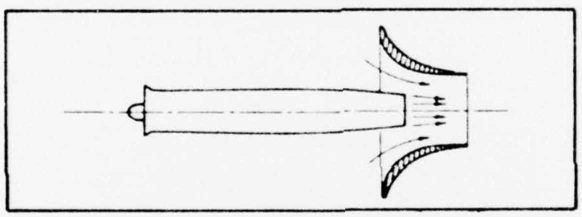


FIGURE 3. Elementary Jet Ejector for Thrust Augmentation.[2]

A number of factors are related to the disk loading. Clearly, increasing velocity of the exhaust or slipstream gases results in increased noise, an increased tendency to erode the surface beneath the aircraft, and to kick up dust, spray (if over water), loose objects, and the like. The increasing energy represented by the higher velocity also represents increased power requirements with attendant increased fuel consumption.

A more subtle correlation with increasing disk or exit area loading is a decreasing resistance to changes in the vertical velocity of the aircraft. These velocity changes, while small relative to the downward air velocity generated by a helicopter rotor, are still significant; the vertical forces on the rotor change such as to resist the motion. The effect is much less pronounced for the propeller, and essentially nonexistent for the ducted fan or jet. The low disk loading helicopter is

[2] Barnes W. McCormick, Jr. *Aerodynamics of V/STOL Flight*. New York, Academic Press, 1967.

inherently more stable in its vertical motions than the high exit area loading, jet-lift V/STOL.

In summary, the lowest disk loading is preferable if hovering and low-speed flight are to be the major use of the machine. And, indeed, helicopters are near ideal for search and rescue missions, landing in confined spaces, etc. The helicopter rotor can generate more downward thrust for a given level of installed power than any other means.

But the helicopter is limited in top speed; the tips of the advancing rotor blade approach sonic velocities (therefore greatly increased drag), while the retreating blade tends to stall. The result is a rapid loss of efficiency (loss of lift, increased requirements for power), with increasing speed. The advancing versus retreating blade differences in the helicopter are overcome in the Tilt Rotor Aircraft (Figure 1a). Even so, the top speed is still limited by sonic velocity at the rotor blade tip. If the speed capability is to be increased, the disk size must go down to avoid compressibility effects. Thus, the disk loading increases. The spectrum of increasing disk loading and decreasing disk areas progresses from the helicopter rotor to the propeller, to the ducted fan, to the turbojet. In each case, limits are reached when local velocities at blade tips approach sonic velocities.*

While low disk loading is preferable for hover and low speed flight, it is not suited for high speed. The high disk loading is best suited for high-speed flight and least suited for hover. This is particularly true for long hover times because of high fuel consumption.

In making his compromises, the designer has two essential options. The first is to use separate lift and propulsion devices, the former being of a lower disk loading than the latter. The aerodynamic design must accommodate the relatively bulky, low disk loading thrust generator and the drag it produces at the higher cruising speed unless retracted or otherwise "stowed." On the other hand, the installed power and associated hover fuel consumption can be less.

The second option is to rely on high exit area loading for lift as well as propulsion. The bulk is lower, which is advantageous for sonic and supersonic capability, but the fuel consumption is higher. Mission procedures and vehicle design for takeoff and landing must minimize the time in conversion and hovering flight to hold fuel consumption to reasonable levels. In sum, the disk loading used for lift tends to be dictated by the intended speed capability of the aircraft; it will increase as the top speed goes up.

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* Even the turbojet-powered aircraft with its supersonic speed capability in some designs must maintain the gas flow velocities through the rotating turbo machinery at subsonic levels.

ENGINE FAILURE

A major consideration in the design of any aircraft is what happens in the event of an engine failure — particularly if it happens in a critical flight regime such as takeoff or landing. These considerations often "design" the aircraft in that the number of engines, their location, etc., depend upon the customer's desires for aircraft performance in the event of a failure. Thus, loss of a commercial airliner in the event of an engine failure during takeoff is clearly unacceptable. For a single-engine lightweight fighter it will be sufficient to guarantee that the pilot can safely get out. Most aircraft designs (the helicopter is a special case) fall between these extremes.

For the V/STOL aircraft, similar considerations are applicable. Thus, loss of an engine in conventional flight poses problems no different than for CTOLs. Engine loss in a multiple-engine V/STOL in partially thrust-borne flight may occur at an altitude and speed which allow acceleration to fully wing-borne flight. However, for V/STOLs in the hovering and low-speed transition modes of flight, the loss of an engine should not result in the pilot's losing attitude control, although it may result in a forced landing or a crash. Maintaining attitude control to at least allow the crew to escape even if the aircraft is lost is therefore a governing factor in V/STOL aircraft design.

For all but the jet-lift V/STOLs, the design practice is to use interconnecting shafting between the several rotors, propellers, or fans, with the engines all supplying rotary power to the common shaft through clutches which permit the failed engine to be disconnected. This is the case in Figures 1a, 2a, and 2b; each aircraft can lose an engine and maintain attitude in hovering flight. Sometimes the power is transmitted by means of hot jet exhaust gases flowing through interconnected ducts to the lifting devices, such as in the XV-4A (Figure 2d) and the so-called gas-coupled fans of which the XV-5 is an example (Figure 2c). The principle in all cases is to maintain thrust balance on all active lifting devices so that, at least, pitch and roll attitude control is maintained, even if the available lifting thrust does not permit the pilot to hold altitude.

For jet-lift V/STOLs having several engines, these interconnects are not practical. The designer has two options. He can locate the engines centrally such that the loss of any one engine does not result in moment imbalances greater than the control system can handle. Or, he can arrange automatic compensation for the failure, e.g., by automatically reducing throttle setting on the "live" engines. Both approaches have been used in past jet-lift V/STOL designs to avoid rapid attitude upsets in the event of engine failure.

For single-engine helicopters, loss of power need not mean loss of the aircraft, depending upon the speed and altitude when the engine fails.

The pilot has some few seconds to reduce the pitch angle of the rotor blades, thereby reducing rotor drag. This avoids loss of rotor speed. The helicopter begins a relatively rapid descent because of the lift loss, but maintains rotor rpm in a mode of operation called autorotation. Near the ground, increasing rotor blade pitch at the correct altitude will slow both the sink rate and rotor speed such that the helicopter lands safely. In effect, the rotational energy stored in the rotor and maintained in descent is dissipated in a manner to provide emergency control capability.

However, to accomplish this requires that the helicopter be outside the "dead man's curve." This is a region of speed and altitude within which the maneuver to enter autorotation and arrest the sink rate is no longer possible; the helicopter crashes because of insufficient forward speed and/or altitude. The helicopter carries no ejection seat because upward ejection through the whirling rotor is not possible.* Successful escape (jumping out) is extremely problematical inside the dead man's curve--so much so that helicopter crews usually carry no parachutes. This situation is changing; escape systems have recently been developed for certain research helicopter applications, and a similar system is currently under development for a production helicopter.

CONVERSION METHODS

To convert V/STOL aircraft from a purely hovering mode of flight to wing-supported flight requires two things. First, the thrust direction is altered from the vertical to the horizontal; and second, the thrust magnitude is changed from that necessary to support the aircraft weight to that required to overcome aircraft drag at the cruise airspeed. Between these extremes, both the magnitude and direction of the thrust vector must be modified to suit the desired rate of acceleration and buildup of aerodynamic lift on the wings. Similar considerations govern the magnitude and angle of the thrust vectors when decelerating from conventional flight to thrust-supported flight — the rotation being from the horizontal to the vertical. These functions are carried out by the pilot, perhaps with the assistance of automatic scheduling devices.

The means used for rotation of the thrust vector can be assigned to one or more of four categories[3]:

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* This deficiency is overcome in the Tilt Rotor Research Aircraft of Figure 1a, which does have ejection seats.

[3] John P. Campbell. *Vertical Takeoff and Landing Aircraft*. New York, Macmillan, 1962.

1. Aircraft Rotation — The entire aircraft is rotated, the thrust generator (jet, ducted fan, propeller, rotor, etc.) being fixed to the aircraft.

2. Thrust Deflection — The slipstream or exhaust from the thrust generator is deflected from the horizontal to the vertical and vice versa.

3. Thrust Rotation — The thrust generator is rotated with respect to the aircraft.

4. Separate Lift and Propulsion — The thrust generators are specialized for either lift or propulsion, and the relative thrust magnitude of each type is altered to produce the effective rotation of the total thrust vector.

Combinations of these techniques are also used and, in fact, are the rule. Thus, aircraft rotation over a small range can always be used to vary the wing-generated aerodynamic lift and change the thrust direction. The terminology "lift jets," "cruise jets," and "lift-cruise jets" refers to thrust generators (jets, in this case) used for lift (only), cruise (only), and both lift and cruise (by means of rotation, deflection, or a combination of both), respectively. Similar terminology is used for ducted fans.

CONTROL FORCE AND MOMENT GENERATION

In V/STOL aircraft in hovering or conversion flight the control forces are generated by means other than conventional control surfaces. Further, the means used are intimately connected with the lift and propulsion scheme used. Generally speaking, the magnitude and/or the direction of the thrust force is varied to produce the pitching, rolling, or yawing torques required for control.

Consider the XC-142 tilt-wing V/STOL shown in Figure 2a. In hovering or low-speed flight the wing is tilted to the vertical and the lift is provided by the four propellers. A smaller, vertically oriented propeller at the rear provides pitch control by means of varying the collective pitch of the propeller blades, and hence the thrust produced. Roll control is provided by varying the collective pitch of the main propellers in a differential fashion; propeller blade pitch is increased on one wing and decreased on the other. Yaw control is produced by differentially deflecting the conventional wing trailing edge control surfaces which are immersed in the propeller slipstream — thrust deflection.

The Harrier aircraft, Figure 1b, has centrally located propulsion; the single engine exhausts through four nozzles located under the wing and close to the center of gravity. The attitude control torques which would be possible with this arrangement (presuming each nozzle to be throttleable) are relatively small because of the short distances between the nozzles and the aircraft center of gravity. Consequently, a separate arrangement of control system ducting is used to provide the control torques. Air from the compressor of the engine is routed through pipes (called "puff pipes" in the Harrier) to controllable nozzles located at the nose, tail, and wingtips. Progressive opening of these nozzles varies the local thrust produced. Two downward-directed thrusters at the nose and tail control pitch; upward and downward directed jets on each wingtip control roll. Two laterally directed jets at the tail control yaw.

In the helicopter rotor, the pitch of the rotor blades can be varied not only simultaneously, as in a propeller for control of lift, but also differentially, so that the rotor blades on one side are at a greater angle of attack than those on the other. More lift is generated on one side of the rotor disk (circular area swept out by the rotor blades) than the other. Simultaneous changes are referred to as changes in collective pitch — hence the term "collective" for the up-and-down control in a helicopter. Differential changes are referred to as cyclic pitch; the pitch of the blade varies cyclically as it travels around the hub. These changes are controlled by the helicopter's center stick; thus the reference to "cyclic stick" or simply "cyclic." The modulation of rotor blade pitch can be from side to side (generates roll torques) or fore and aft (generates pitch torques).

For most helicopters the effect of cyclic blade inputs is to "tilt" or rotate the thrusting rotor disk, by virtue of either "teetering" or "flapping" hinges between the rotor blade and the rotor hub. The resulting tilted thrust vector acting above the helicopter's center of gravity then provides the desired pitch or roll control moments. For "rigid" rotors lacking such hinges the control moments are created directly by the asymmetric lifting forces on the rotor disk.

A major requirement for all V/STOL control system designs (here defined as the control force generators, the pilot's controls and the subsystems connecting the two) is the proper blending of the control forces produced by the aerodynamic control surfaces and the hovering control force generators as the effectiveness of the former decreases simultaneously with decreases in the airspeed. The conversion between aerodynamically supported (and controlled) flight and thrust-supported (and controlled) flight involves not only changes in the thrust angle and thrust magnitude but also in the relative effectiveness and use of the several "surfaces" in the flight control system. In the following two sections of the report these "internal" aspects of the V/STOL aircraft configuration, that is, propulsion and flight controls, are discussed separately. However, it should be clear that both aspects are more intimately related in the V/STOL than is generally the case for conventional aircraft.

GAS TURBINE ENGINES

Management of the propulsion system is a more significant aspect of the pilot's role in V/STOL aircraft than in CTOLs, primarily because of the reliance on propulsive forces for lift during transition and hovering flight. The pilot's control of thrust in a V/STOL is somewhat akin to a direct lift control in a conventional airplane; the motion responses are immediate and can be quite sensitive to small pitching or rolling moments.

The nature of the task is dependent on the characteristics of the propulsion system which in most cases depends on some variant of the gas turbine engine. These engines provide modern technology's best compromise among the conflicting requirements for light weight, high power, efficiency, and flexibility demanded in aircraft applications. The high power-to-weight ratio of the gas turbine engine is what makes most helicopters and all higher disk loading V/STOLs feasible. But because they are relatively unfamiliar to most readers and because they are available in so many forms depending upon the precise application, it is appropriate to briefly describe the propulsion technology they represent.

SINGLE SPOOL TURBOJETS

The simplest form of gas turbine engine is the single spool turbojet, a cross section diagram of which is shown in Figure 4. Its principle of operation is analogous to that of a fuel-injected reciprocating engine;

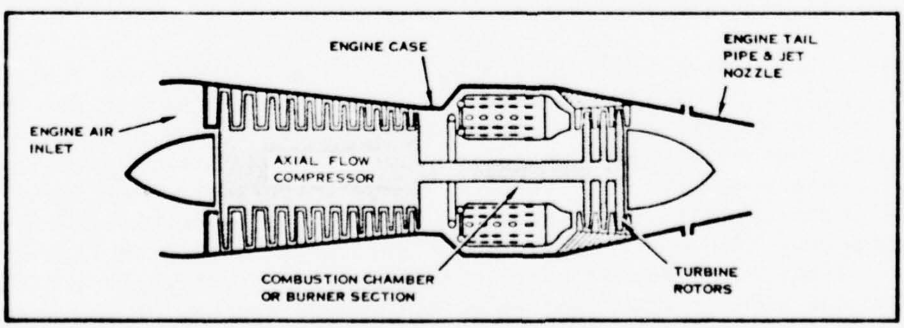

FIGURE 4. Single Spool Turbojet Engine.[4]

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[4] This figure and engine cross-sectional diagrams which follow are all adapted from *The Aircraft Gas Turbine Engine and Its Operation*. East Hartford, Conn., Pratt & Whitney Aircraft, May 1974. (PWA Oper. Instr. 200.)

air is taken in and compressed, fuel is injected and the mixture ignited, and energy extracted as the burning gases expand. However, in contrast to the reciprocating engine, the gas flow is continuous throughout the combustion cycle rather than intermittent. And, in the case of the turbojet, the useful power comes from the high velocity gases exhausted to the rear rather than a rotating shaft. In other design variations to be discussed later the expanding gases drive additional turbine rotors with rotational energy being extracted therefrom.

The turbojet engine operates as follows. Air taken in on the left (Figure 4) is compressed with an air compressor which operates not unlike a supercharger for a reciprocating engine. In the example shown, air is compressed through a sequence of axial flow (so-called because air travels parallel to the axis of rotation) stages. Each stage consists of a set of guide vanes (usually fixed) called the stator and a set of rotating vanes or blades called the rotor. The air is forced into each succeeding stage at essentially the same velocity but at higher pressure and density. At the right-hand end of the compressor (Figure 4) the air is delivered to the combustion section of the engine where the fuel is injected and the mixture burns like a blowtorch (electrical ignition is needed only to start or relight the engine). The expanding gases pass through another sequence of fixed guide vanes and rotating turbine blades where energy is extracted (about 75 percent of the total) to drive the compressor which is fixed to the turbine shaft. The hot gases are then exhausted at high velocity out the tail or nozzle pipe at the right (Figure 4) producing thrust.

The thrust comes from the momentum which has been added; the momentum (mass multiplied by velocity) of the air, unburned fuel, and combustion products exhausted at the rear is much larger than the momentum of the air taken in at the front. The difference appears as thrust according to Newton's Second Law of Motion.

Aerodynamic principles are in force in the operation of the turbojet. The blades and guide vanes of the compressor rotor and stator, and of the turbine rotor and stator, are all airfoils — specialized in their shape, size, and orientation for the functions they perform and optimized over a relatively narrow range of local gas flow conditions. Within this range, the gas turbine engine is very efficient; outside this range the compressor blades can stall (resulting in compressor "surge"), the turbine can overspeed, or the compressor air flow can "choke" (i.e., become supersonic). Considering the range of inlet airspeeds, air densities, and temperatures, the full range of thrust requirements from idle upwards, requirements for starting and shutdown, and the requirements for acceleration and deceleration, i.e., rate of change of thrust, it can be appreciated that maintaining proper local gas flow conditions within the engine is a complex proposition.

TURBOJET VARIATIONS AND THRUST CONTROL

Some of the means used for control of gas flow in the engine are briefly described below:

1. Variable inlet and exhaust nozzle geometry — To provide a more optimum interface between external (e.g., supersonic) speed and internal energy-efficient (sonic or subsonic) speeds in the compressor and turbine sections; primarily used on supersonic aircraft.

2. Variable air bleeds in the compressor — To provide additional internal flow control over the applicable wide ranges of ambient temperatures, pressures, speeds, etc., and to provide a convenient source of high pressure air for all sorts of functions such as reaction control thrusters in some V/STOLs. However, use of bleed air also reduces thrust, in this example lifting thrust, a factor which can adversely affect the pilot's control of altitude in certain jet-lift V/STOLs.

3. Two spool engine (Figure 5) — Another means of optimizing operating conditions within the jet engine is to use two compressors, each running at its own speed. The relative speed can be varied to better suit the intended range of altitudes and thrust produced. Air bleed is frequently used between stages. Engine instrumentation includes both high pressure compressor and low pressure compressor rpm.

4. Variable stator blade angles — Internal air flow conditions within the engine can also be varied by altering the stator blade angles at one or more stages within the compressor.

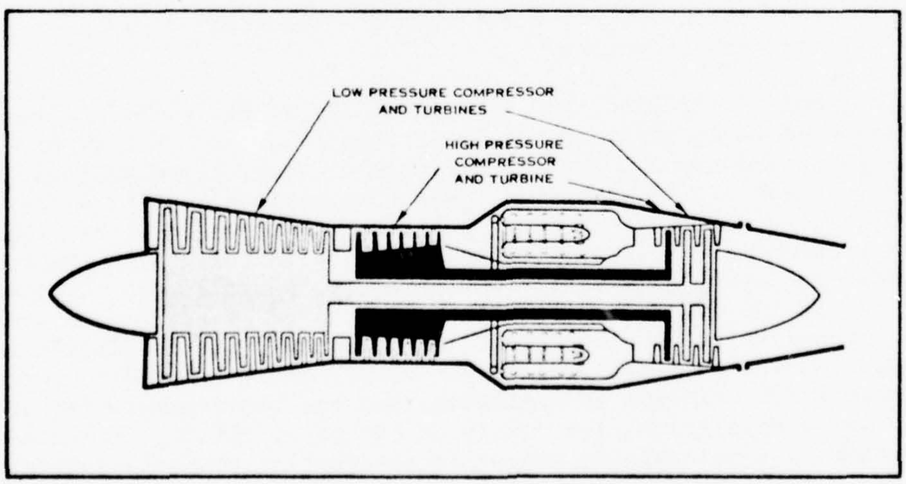

FIGURE 5. Twin Spool Turbojet Engine.[4]

Many of these variations are accomplished more or less automatically, e.g., airbleeds when local pressure exceeds a preset level. Others must be scheduled as a function of external ambient conditions, e.g., inlet geometry as a function of airspeed or Mach number and, perhaps, angle of attack.

The fuel controls on these engines are relatively complex — at least in comparison with the conventional interpretation of a throttle for control of power. The fuel is metered to the burner section in accordance with the pilot's power lever ("throttle") setting and the measured operating conditions within the engine — chiefly turbine rpm, turbine inlet temperature, and engine pressure ratio (EPR). Because turbine inlet temperature is difficult to measure directly it is inferred from temperatures and pressures measured elsewhere, e.g., exhaust gas temperature (EGT). The engine pressure ratio is the ratio of the two pressures measured just downstream of the turbine and just upstream of the compressor. It is proportional to thrust and can be used by the pilot as a thrust indicator in turbojet-powered aircraft.

In setting the throttle to a particular position within the cockpit, the pilot is commanding a closed-loop feedback control system designed for engine thrust control. Not only does it control the thrust, it limits the operating conditions (temperatures, pressures, turbine speed, and internal air flow velocities, which must remain subsonic) to ranges intended by the engine designer. As far as the pilot is concerned, throttle position is often the major indicator of thrust; all the other engine instruments (fuel flow, fuel pressure, engine internal temperatures and pressures, turbine rpm, etc.) act as monitors of proper system operation, much like automobile gauges for coolant temperature and oil pressure.

TURBOFAN, TURBOPROP, AND TURBOSHAFT ENGINES

The turbojet engine described above, perhaps with an afterburner* in military applications, is only one of the numerous gas turbine engine types. There are a considerable number of variations possible, all of which extract additional energy from the exhaust gases by means of additional turbine stages. The amount extracted can range from relatively little to essentially all of the energy left over after driving the compressor. In each case, that portion of the engine which produces the power, that is, the compressor, combustor, and turbine sections of the engine, is referred to as the gas generator or core engine.

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* In an afterburner, fuel is injected downstream of the turbines in the tail pipe where it ignites, further adding to the energy and mass flow of the exhaust.

One variation is to add additional turbine stages and use the rotational energy to drive a propeller or a fan. Figure 6 shows these variations on a twin spool core engine, resulting in turboprop and turbofan engines. The particular turbofan shown here has short fan ducts where the fan exhaust (bypass) is separate from the jet exhaust.

The turboprop engine permits more efficient operation at lower aircraft speeds than the turbojet: the propeller accelerates a much larger mass of air to a considerably lower velocity than the turbojet exhaust. However, a gearbox is required to increase the shaft torque and reduce the propeller rotational speed; the propeller blade tips must remain at subsonic velocities. The tip speed limitation restricts the top speed of the aircraft. The turboprop engine also requires a propeller speed governor to maintain propeller rotational speed and efficiency at optimum levels throughout most of the flight envelope. The governor is a feedback control system which controls propeller speed by changing the collective pitch of the blades; steeper pitch absorbs more power and slows the propeller. Shaft horsepower, rather than EPR, is used to measure engine power.

During the landing approach, where the engine is operating at power levels close to flight idle, the power lever operates in a different mode. Rather than commanding power, it controls propeller blade angle. The propeller speed is allowed to vary.

The turbofan, like the turboprop, engine is also more efficient at lower speeds than the turbojet; unlike the turboprop it is less limited at high speed. The smaller diameter, duct-enclosed fan, perhaps with more than one stage, is designed to maintain air velocities within the fan at subsonic levels largely independent of the airplane's speed. In appearance, it typically is rather like the first one or two stages of an axial flow compressor, only larger. An important design parameter for these engines is the bypass ratio — the proportion of the incoming air which passes only through the fan, relative to the proportion which passes through the engine. High bypass ratio turbofans (say 5:1 or more) generate most of their thrust from the air accelerated by the fan, the remainder from the turbine exhaust.

A common variation is to place added turbine stages on a separate shaft, whose speed is independent of the compressor and main turbine speeds and often regulated separately by a governor. Such an engine is referred to as a free turbine engine. The free turbine shaft drives a gear box (turboprop) or transmission (rotor in a helicopter). Figure 7 shows a single compressor, free turbine drive turboprop engine.

The helicopter application is an example of the turboshaft engine — a gas turbine engine, often of the free turbine type, which drives remotely located propellers, rotors, or whatever (these engines are used

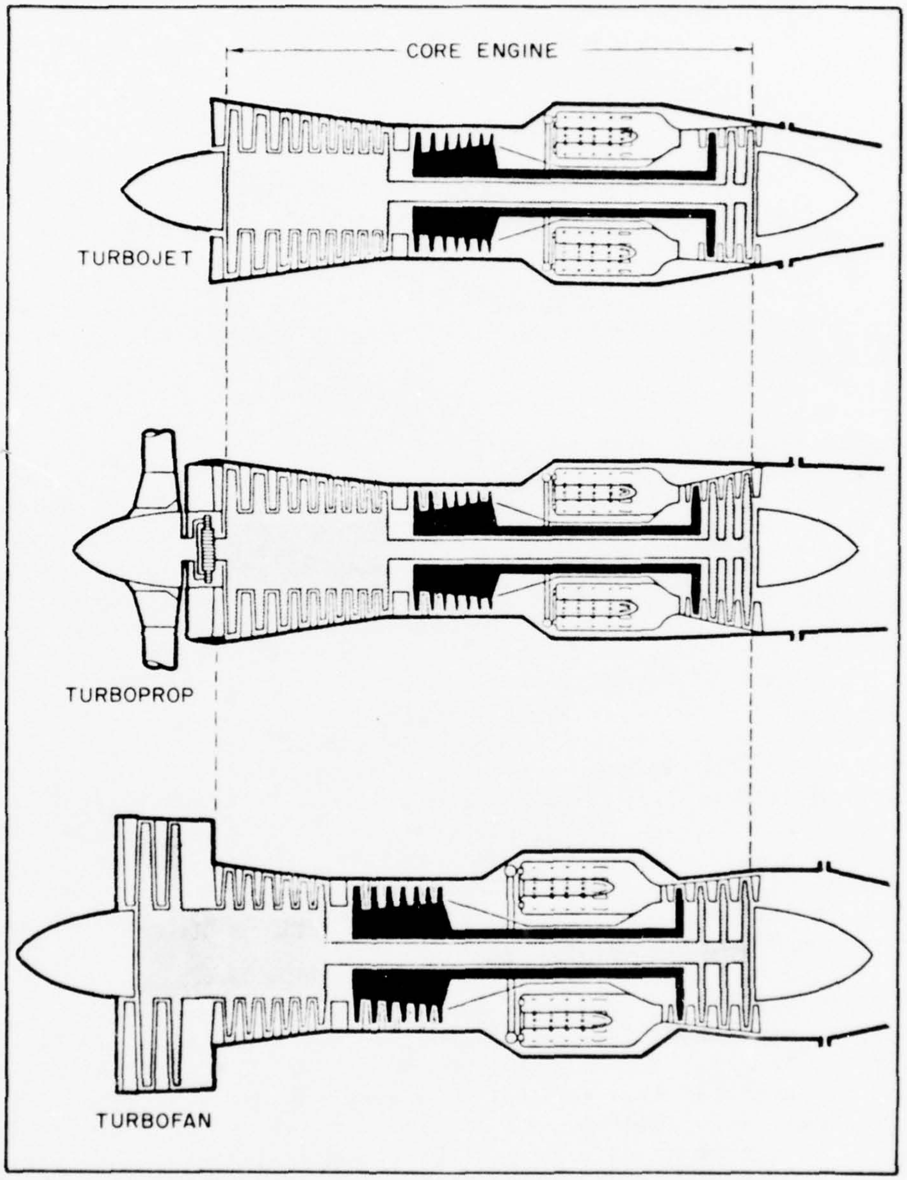

FIGURE 6. Comparison of Twin Spool Turbojet, Turboprop, and Turbofan Engines.[4]

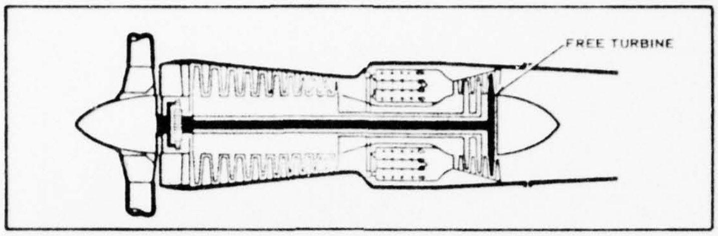

FIGURE 7. Single Compressor, Free Turbine Turboprop.[4]

in industrial applications as well). Power production is wholly at the shaft output with virtually no usable energy remaining in the exhaust gases.

SPECIALIZED ENGINES

A specialized example of a gas turbine engine is the Rolls Royce "Pegasus" (in several versions). It is used in the AV-8A V/STOL aircraft (Figure 1b). This engine is described as a twin spool turbofan engine with rotatable exhaust nozzles. The fan air is exhausted through the forward (cold) nozzles. The jet exhaust passes through the aft (hot) nozzles. All four nozzles are rotated in unison to deflect the thrust from aft to vertical for conversion. Bleed air from the compressor supplies the separate reaction control system. The engine is also unique in that the two spools rotate in opposite directions so that the gyroscopic forces are minimized. The latter is an important consideration for V/STOL attitude control in low-speed flight. The engine has provision for water injection for peak thrust demands; the water adds to the mass of the exhaust gases, increasing the thrust — so-called "wet" thrust — for the heavy demand conditions of takeoff and landing. It also aids in limiting the temperature rise of the exhaust gases, an important consideration for engine life.

Another specialized engine is that used in the XV-5 (Figure 2c). In this engine the exhaust gas flow is routed through a conventional tail pipe for cruise flight or diverted to the fan scrolls (annular rings surrounding the wing and nose fans in this airplane which contain the tip turbine blades) for fan-supported flight. In this mode of operation the engine can be described as a free turbine turbofan engine; the free turbine and fan have a unique configuration and orientation but otherwise function as the description implies.

The separate lift engines used in some jet-lift V/STOLs are also highly specialized. In this case the specialization is less in form and more in the detailed design for high static thrust at relatively low altitudes — the only conditions in which they operate. Their use in a design carries with it additional piloting tasks associated with in-flight engine startup and shutdown.

FLIGHT CONTROL SYSTEM TECHNOLOGY

While the technology represented in the design of a modern aircraft's flight control system is comparable with that of the rest of the airplane, the functioning of the system from the pilot's viewpoint has remained relatively invariant. The function, behavior, and "feel" of the primary (aircraft orientation) and secondary (aircraft trim and configuration) flight controls, together with the responses thereto, are more traditionally based on the capabilities of the human element which of course have remained unchanged. It is therefore appropriate to consider first the elements of a simple "old fashioned" flight control system and their relationships to aircraft behavior. The more complex "modern" systems with entirely different technologies considered next tend to mimic the simpler systems, at least in the cockpit. The section concludes with a brief outline of automatic flight control where one or more pilot control functions are automated.

COCKPIT CONTROLS

The single-engine general aviation aircraft is representative of a simple flight control system. The forces required to move the control surfaces are provided by the pilot through a combination of centerstick* (controls aileron and elevator position) and pedals (controls rudder). There are also trim controls, to be discussed later. There is a throttle control for engine power setting, together with controls for starting the engine. Auxiliary controls make up the remainder of the complement (flaps, landing gear, etc.).

In the light airplane, the centerstick and pedals are connected to the control surfaces by means of a series of pushrods, cranks, pulleys, and control cables. Motion of the stick causes elements of the interconnecting linkage to move which in turn cause motions of the control surfaces. The control system is reversible in that motion of the surface will cause motion of the pilot's control (stick or pedals).

The pilot must supply the forces required to move and hold the control surface (e.g., elevator) against the aerodynamic pressure acting upon it. Ignoring the effects of friction within the control system linkage, the forces required are proportional to the surface deflection and increase

* Yoke/wheel arrangements are also used. Fore-and-aft motion still controls the elevator; steering-wheel-like motions control the ailerons.

with increasing airspeed. Twice the speed means four times the force for a given surface deflection, and so on. If the airplane is mistrimmed, a little nose heavy for example, the pilot must apply back pressure to the stick to hold the elevator in a position other than the zero force, neutral position.

To relieve these forces, a trim system is used. In a light aircraft, it can work through a secondary trim surface called a trim tab located on the primary control surface. Figure 8 shows an example aileron trim tab. When the tab is deflected in one direction it alters the aerodynamic force balance acting on the control surface itself, causing it and the pilot's control stick to move in the opposite direction. The position of the tab is controlled by a secondary control in the cockpit, typically a trim wheel. Rotating this wheel moves the tab and, in turn, the control surface and stick to a new neutral position. The pilot is now relieved of the necessity of holding continuous force on the controls to keep the airplane in straight and level flight. Further, the new position of the primary control (stick or pedals) is indicative of the control surface trim position.

The function and operation of the cockpit trim controls described here is identical to what occurs in sophisticated flight control system

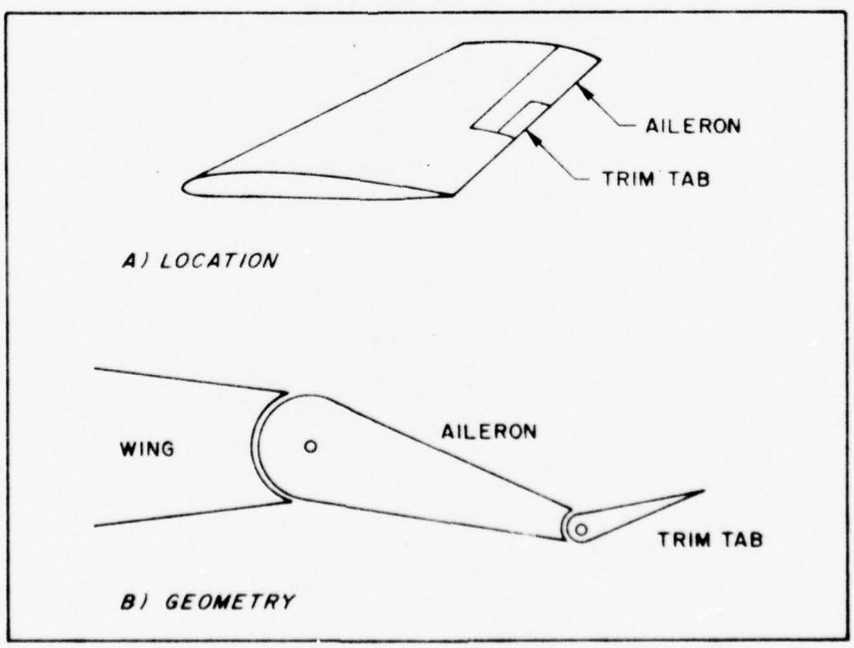

FIGURE 8. Aileron Trim Tab.

designs described as having parallel trim.* In these systems, the aileron and elevator trim is often thumb-controlled by deflecting a "coolie hat" — a four-position, spring-loaded to center, switch on the pilot's stick grip (Figure 9). Deflecting the "hat" causes the control surface (and the stick with a parallel trim system) to move at a slow rate. When the switch is released the motion stops.

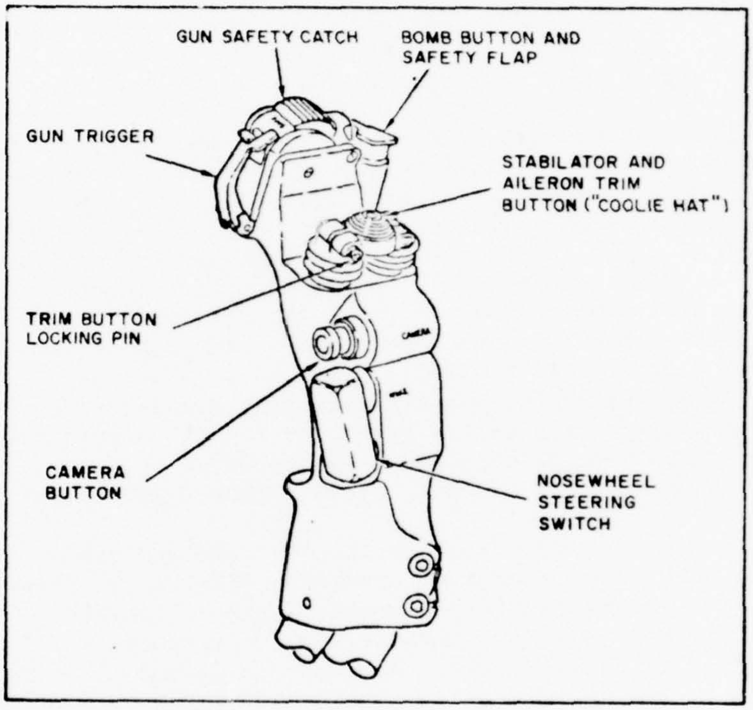

FIGURE 9. AV-8A Centerstick Grip with Auxiliary Controls.[5]

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* The term "parallel" refers to the fact that the stick and the surface move together. Series trim is also used. The term "series" means that the trimming device is between the cockpit control and the surface so that its operation results in control surface motion but no corresponding motion of the stick. Series trim systems are sometimes criticized on the ground that the pilot does not know what the surface trim position is without looking at a panel indicator. Consequently, he does not know how much additional surface deflection (control power) is available for maneuvers.

[5] Naval Air Systems Command. *NATOPS Flight Manual, Navy Model AV-8A Aircraft*, 19 February 1975; Change 1, 15 September 1975. (NAVAIR-01-AV8A-1.)

In contrast to the centerstick (and to a much lesser extent the pedals), the secondary flight controls in the cockpit of CTOL aircraft are adjusted relatively infrequently. These controls include the throttle, flaps, landing gear, and controls for taxiing the aircraft (e.g., left and right main landing gear brakes, to permit ground steering by differential braking). Of these, operation of the throttle is the most germane to the present discussion.

In a conventional, high-performance airplane, the throttle is normally located on the pilot's left, is continuously adjustable, and is held in position by friction. The friction forces typically are adjustable to suit an individual pilot's preferences. Because certain power settings are used relatively frequently, there may be detents, or other means, by which the throttle can be set to a desired position without visual reference to the throttle position. If there is more than one engine the installation of the several throttles is such that they can be moved as one, i.e., they can be ganged together. There are also "fine adjustments" between each throttle to establish identical engine rpm and/or economical cruise operation. Because inadvertent change of the throttle setting during the critical operations of landing or takeoff could be disastrous, the control is typically provided with a "guard" which prevents throttle motion beyond specified limits, unless the guard is deactivated. The deactivating device takes the form of a button or trigger-like lever on the throttle which must be depressed or squeezed before the throttle can be moved, for example, below flight idle.

In the helicopter, the nature of the aircraft and its unique flying capabilities introduce a number of changes. First among these is the addition of another primary flight control, the collective. This typically takes the form of an inclined-from-the-horizontal stick, located to the pilot's left (Figure 10). The stick is pulled up or pushed down

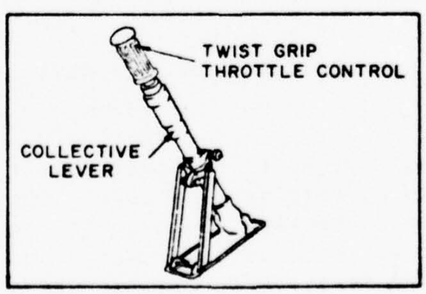

FIGURE 10. Helicopter Collective Lever.[6] The lever is shown at the upper limit of its travel.

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[6] Jacob Shapiro. *Principles of Helicopter Engineering*. New York, McGraw-Hill, 1956.

against retarding friction to increase or decrease the rotor blade collective pitch, hence the helicopter's lift. Because altering the rotor pitch changes the load on the engine(s), the power must be adjusted simultaneously with the collective. This is provided in simple helicopters by installing a twist grip on the end of the collective lever which acts like a throttle. The pilot can then make collective and power adjustments simultaneously. In more complex systems, the coordination of engine power and rotor blade pitch is accomplished by a rotor speed governor which operates much like the governor on a turboprop engine. The throttle control is replaced by a governor control and an engine trim (beeper) switch. Sometimes a separate throttle control is provided.

The control properties of the helicopter are also somewhat different from a conventional aircraft. Changes in attitude at low airspeeds result in translation along the ground, and not a climb or dive. Thus, takeoff is accomplished by increasing power, raising the collective, and pitching the helicopter nose down — the helicopter moving forward with pitch, upward with collective. Frequently, the feel characteristics in the cyclic stick used for controlling attitude are unconventional in that there is little, if any, force tending to return the stick to a neutral position. A helicopter pilot flying close to the ground has both hands on the two primary controls — cyclic and collective.

The design of the cockpit controls in a V/STOL aircraft has features in common with both the conventional airplane and the helicopter. In addition, it has controls for the conversion. While there is considerable traditional basis for the design of controls for either conventional or hovering flight, the situation is not so clear for the conversion controls, or how they relate to the throttle or collective. Consequently, there has not evolved a "universal" design for these controls in the V/STOL.

Design practice is heavily influenced by the nature of the particular lift/propulsion system concept used in the aircraft. Usually, the conversion controls are arranged to control thrust magnitude and thrust direction. The magnitude is controlled with a throttle or a collective; the angle is controlled with a fingertip control on the thrust magnitude lever, or with a separate lever as in Figure 11. The fingertip control arrangement, such as a thumbwheel or trim button, is used when the conversion angle is controlled at a constant rate and where several surfaces must be scheduled in a coordinated fashion as in the tilt wing or tilt duct aircraft of Figures 2a and 2b.

In cases where separate lift and propulsion devices are used there are frequently separate controllers in the cockpit. Thus, there can be two sets of throttles, one of which controls lift, the other propulsion. In some aircraft there is a discrete changeover or sequencing from one mode or operation (thrust) to the other (lift), which is frequently controlled by a programmer or scheduler set in motion by an appropriate switch in the cockpit.

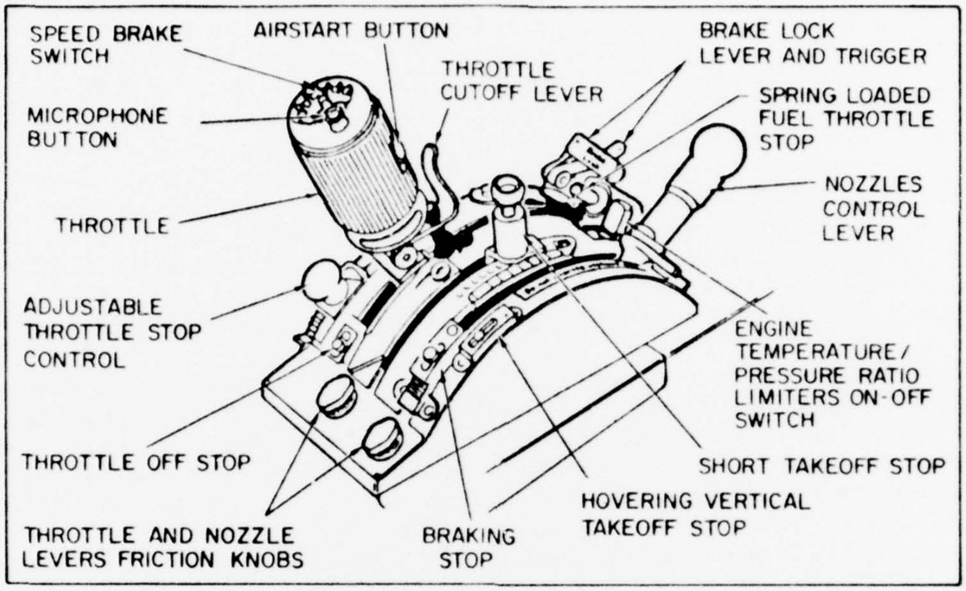

FIGURE 11. Throttle and Conversion Controls for the AV-8A.[5] The adjustable stops on the nozzle control lever are present to suit desired nozzle trim positions. The nozzle lever position shown here is for cruise flight (nozzles directed aft). The cutoff lever on the throttle must be squeezed to pull the throttle to its fully aft, engine shutdown position.

FLIGHT CONTROL SYSTEMS

As the size and performance capabilities of an aircraft increase, be it conventional or V/STOL, the forces required to deflect and hold control surfaces do also — to the point where the pilot no longer has the capability of providing the necessary control forces. The systems which have evolved in response to this situation are hydromechanical in nature, wherein a portion (power boost) to all (fully powered) of the force required to move and hold the control surfaces is generated hydraulically. The hydraulic valves are controlled by the stick, pedals, or collective through a mechanical linkage. These systems are quite analogous to automotive power steering or power brakes.

One major consideration in the design of such systems is the provision of adequate control "feel." As the force amplification increases, the sensation of surface forces felt in the stick decreases. The fully powered systems are non-reversible in that forces applied to the surface cannot move the stick. The only controlling forces are those required to move the linkage and activate the hydraulic valves. Consequently, the pilot would have no appreciation of the control effort being applied without the incorporation of "artificial" feel features. These are devices which provide the pilot with some measure of the control force sensations which are otherwise lacking in the powered flight control system.

Besides providing feel characteristics, such systems frequently include devices which inhibit the pilot from demanding too much maneuvering performance of the aircraft. A common device is the bobweight, which increases the stick forces proportionate to maneuvering normal acceleration, as in tight turns and pullups. "Stick pushers" are sometimes used for a similar purpose; these are devices which apply a forward stick force when the aircraft approaches stall. More common is the stick shaker which provides a tactile warning of the aircraft's approach to stall. Horns and lights are sometimes used to warn of an approach to an unsafe flight condition.

Flight control systems frequently include devices which augment the inherent damping, stability, and/or controllability characteristics of the aircraft. These are actually feedback control systems where the quantity being controlled is measured. For example, the rate at which the aircraft is rolling. They are mechanized by sensing the motion with an appropriate instrument, a rate gyro in this example, and using this signal to command a small actuator (hydraulic, pneumatic, or electric) servo which positions the control surface through a series link in such a way as to resist the motion.* Other devices similar in mechanization and purpose are used in other control axes and include the pitch damper and yaw damper. Other sensors, for example accelerometers, are used with appropriate equalization to create the sideslip stability augmentor (acts to resist sideslip) and vertical velocity damper (used in the XC-142, Figure 2a).

In addition to these feedback devices there are also feedforward loops which act to assist the pilot in coordinating multiple controls, that is, to improve the control response characteristics. These include various interconnects such as the aileron- or stick-to-rudder interconnects used to improve the responses in turning maneuvers, and throttle-to-elevator interconnects used to minimize the pitch-with-power characteristics exhibited by aircraft in which thrust changes would otherwise result in pitching moments.

A paramount consideration in the design of such systems is that of reliability. Here there are two basic approaches: system design which

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* The term "series" is used in the same sense as in the earlier footnote on trim systems, that is, the control surface motion is not reflected in a motion of the pilot's stick. The pilot is not directly aware of the augmentor's activity, because the stick does not move.

provides for "fall back" capability in the event of a failure; or redundancy in the design at a level which effectively precludes single, dual, or triple failures (depending on degree of redundancy) from compromising the pilot's control of the aircraft. There are, of course, intermediate approaches to the design of flight control systems which depend upon the details of the intended mission and the cost/performance compromise intended. The following paragraphs outline the extremes.

In the first approach the design of the flight control systems allows some measure of pilot control in the event of a failure. The situation is analogous to certain failures in power steering or power brakes of an automobile — some measure of control is retained. Thus the series servos used for stability and response augmentation have limited authority; even if a failure causes the servo to go to the fullest extent of its travel ("hardover" failure), the pilot can override its effect on the control surface by deflecting the cockpit control in the opposite direction. The aircraft will undergo transient motions in the meantime, and the stability augmentation feature is, of course, lost from that point onward. This relatively simple approach is applicable to those cases where the required, augmented improvement in the aircraft response characteristics is relatively small. If the augmentor fails, the resulting transients and subsequent response character are controllable at an acceptable level of effort. The aircraft may even be able to complete its mission, and is certainly capable of returning to its base.

The second approach, using redundant elements in the system design, is applicable in those cases where a system failure would compromise the mission, perhaps even the aircraft's survival. In these cases the aircraft's characteristics are such as to render it extremely difficult, if not impossible, to adequately control the aircraft in the event of a failed flight control system. Full-authority augmentation — capable of controlling the airplane's control surface over the full range of its travel — is a case in point; dual redundancy at least is required to prevent full-authority hardover (therefore uncontrollable) failures. Such augmentation, and concomitant redundancy, is used, e.g., in modern supersonic jet airliners, which are sometimes inherently unstable (due to an aft center of gravity). In cases such as these, automation of the flight controls is no longer describable as a pilot aid, but rather as an essential feature of the aircraft design much as the structure or power plant.

This example also serves to illustrate a fundamental characteristic of a feedback control system — the ability of such a system to desensitize the airplane's motion responses to both externally and internally generated disturbances. A high-gain feedback control loop having high authority can make the airplane's motion responses more or less independent of the disturbances, for example, those induced by the propulsion system, up to the point where the magnitude of the disturbances causes the control authority of the feedback loop to be exceeded. The high authority of the loop also means that it cannot be allowed to fail, e.g., go hard over, as this would likely be catastrophic to the aircraft.

AUTOMATIC FLIGHT CONTROL

In addition to the force amplification, control "feel," stability and response augmentation features described thus far, the flight control system can have a number of additional features which act to relieve the pilot of one or more of his control tasks, at his option. Most of these can be considered to be regulators. Thus, the automatic flight control system (autopilot) can incorporate attitude hold, heading hold, altitude hold, etc., features which operate through the primary flight control system. These devices require additional sensors, e.g., attitude gyro, directional gyro, radar or barometric altimeters, etc., for the motion quantities being controlled. They generally operate through parallel servos; the cockpit controls move in response to the autopilot action, thereby affording the pilot a means of monitoring autopilot activity. The pilot need only select the attitude, heading, altitude, or whatever desired, and the system does the rest.

Other regulatory systems operate through the secondary flight controls, almost universally through parallel servos. These include autothrottles (airspeed hold or trim-angle-of-attack hold devices) and governors (propeller or rotor rpm regulators). Setting of a suitable reference condition is usually the pilot's responsibility, but is sometimes implicit in the design of the automatic control.

Another type of automatic control is the scheduler. This device alters the trim setting or position of one control in response to a change in some sensed motion quantity or other indication of the trim flight condition. A typical application is flap setting change scheduled as a function of airspeed and perhaps power setting. Here the system typically functions through a parallel servo; the cockpit control moves in concert with the control surface. Another example has already been noted in connection with engine thrust control — that of automatic scheduling of the air intake geometry with angle of attack and Mach number in supersonic aircraft. In this instance, there may only be a panel indicator of the scheduler's operation. A third example, taken from the XC-142 aircraft illustrated in Figure 2a, is a mechanical conversion scheduler or "mixing box" which provides both propeller blade pitch and flap angle changes, as functions of the wing tilt angle.

Safety of flight with parallel servo devices is assured through a variety of techniques, depending upon the potential effects of a failure in the system. These system concepts lie somewhere in the spectrum between limited authority, single thread (i.e., no redundancy) systems to full-authority, highly redundant systems. Typically, the parallel servos are automatically disconnected when a moderate force is applied to the cockpit control. The force is set high enough to avoid nuisance disconnects caused by the pilot's keeping his hands on the control, which he will do in any case. In other cases, switches for disconnecting the system will be located on the centerstick grip or the throttle. Switches for activating the system, reference setting controls, monitor lights, etc., are on the instrument panel.

In some applications, self-monitoring features may be incorporated which disconnect the device upon exceeding some design error tolerance and advise the pilot of the situation (alarm light, instrument flag, horn, etc.).

Another feature these systems use goes by the general term of built-in test (BIT). These are features which, on one level, allow the pilot to verify subsystem integrity before using it and, on another level, allow malfunction identification and isolation for maintenance purposes. The functional complexity of these automatic controls is in large measure due to the various self-monitoring, self-checking, or testing features which are incorporated — so much so that the simplest portion of the system is often that which actually provides the automatic control action.

Given the range of automatic control devices described in the preceding paragraphs, the pilot need only translate guidance and navigational information into appropriate reference settings for the aircraft to fly itself for much of the time. Even this task can be placed under automatic control, and frequently is for critical applications such as blind landing.

An automatic landing system requires a means of generating guidance information (location, velocity, etc., of the aircraft relative to the desired landing spot), translating this information into autopilot commands (a computer), and a coupler which couples these commands to the aircraft autopilot. The entire system is a closed-loop feedback control system which functions to regulate the aircraft's path and speed along the final approach to landing. The Navy's Automatic Carrier Landing System (ACLS) and commercial aviation landing systems with Category III capability (automatic all the way to touchdown) are examples. Both are motivated by weather conditions where the pilot has insufficient visibility for a safe landing under manual (pilot) control.

The flight control technology outlined above carries with it a variety of small controls (switches, pushbuttons, etc.) and associated panel indicators (e.g., indicator lights of the mode of operation selected), all of which are required in order to fly the aircraft. The pilot's task is more complex by virtue of the number of options open to him for control and the possible courses of action to take depending upon the nature of the panel indications (e.g., failures, warning lights).

V/STOL RESPONSE QUALITIES

Preceding sections of this report have concentrated on the hardware aspects of V/STOL technology. While there have been frequent references to piloting requirements for monitoring or controlling the aircraft and various of its subsystems, these aspects have not been examined as an integrated whole. In this section the pilot's role is briefly examined, followed by a description of those V/STOL response qualities falling out of the technology described earlier which contribute to the excessive workload problem noted in the Introduction.

THE PILOT'S ROLE

The pilot's role in flying the V/STOL aircraft consists of a number of functions, all of which have their counterparts in conventional aircraft. They can be briefly listed as follows:

1. Configuration scheduling; lift/thrust management
2. Attitude stabilization
3. Path, speed, and position control or regulation
4. Subsystems management

Each of these functions is, however, more demanding than the counterpart in conventional aircraft. The pilot has more things to control which are changing faster and which must be attended to in shorter periods of time.

Excessive demands on the pilot are in large measure a consequence of characteristics inherent in the V/STOL concept. Indeed, it quite often happens that quite dissimilar V/STOL configurations exhibit strong similarities in behavior in response to the controls because of similarities in the underlying physics governing the aircraft's motions. This is why the workload problem and the pilot's role can be addressed, at least in part, without configuration-specific considerations.

CONFIGURATION SCHEDULING

During a landing approach, for example, the pilot desires to maintain a desired flight path while the configuration and airspeed are changed for landing (gear, flaps, throttle setting, etc.). In the V/STOL the changes in thrust angle and magnitude are much more profound, and typically result in "ballooning" above the desired glide slope upon initiating conversion. Both path (or altitude) and speed changes result from changes in pitch attitude, throttle setting, and thrust angle; the appropriate technique which accomplishes the deceleration while minimizing the path disturbances and maintaining flight safety is relatively complex, and usually the result of carefully worked out sequential procedures. The "flexibility" provided by the redundant controls is lost in the necessarily restrictive procedures required for lift and thrust management during transition.

STABILITY AND CONTROLLABILITY

More aircraft degrees of freedom must be stabilized and controlled than is typical for conventional aircraft. In the conventional flight regime, the pilot's control of vehicle attitude is usually sufficient to guarantee stability of the motions in the translational degrees of freedom — lateral drift, forward speed, and rate of climb or descent.* In V/STOL aircraft in transition or hovering flight, attitude control is insufficient more often than not; the translational motions do not "take care of themselves," are often unstable in their responses, and require more precise control to execute the desired maneuver (e.g., landing on the moving deck of a ship). The rotational motions, that is, motions in pitch, roll, and yaw, can also be unstable in their responses, particularly when the aircraft is in close proximity to the ground. The causes here have already been noted: flow turning forces and moments in the lift/propulsion system; and ground effects caused by the interaction of high velocity downward flow with the ground.

A helicopter in hover is statically stable in attitude because the center of lift, the rotor, is above the center of gravity. It is frequently dynamically unstable in attitude in that pitch or roll oscillations will exhibit increasing amplitude with time unless the pilot intervenes. If the rate of amplitude increase is not too rapid, he can control or dampen the oscillations to an acceptable amplitude.

A hovering jet-lift V/STOL, on the other hand, is neutrally stable, perhaps even statically unstable, in attitude; the center of lift is coincident, perhaps even below, the center of gravity. The divergent tendency may be aggravated by ground effects or flow turning moments. The pilot must detect and correct the divergence early; if he does not, he may run out of control power and be unable to recover control. The situation is something like balancing a broomstick on end. It is easy to recover if the broomstick is long (slow divergence) and it is not allowed to tip or fall too far, and difficult if the broomstick is short (rapid divergence).

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* When this is not the case, the translational motions must be controlled separately, using a different control. Instability in the path and speed responses often occurs for jet aircraft during landing approach and is separately controlled through the throttle.

Stability in the linear degrees of freedom assume greater importance in V/STOLs relative to conventional airplanes. In contrast to CTOLs, altitude motions are controlled separately; recall the earlier discussion of the relative stability of vertical motions in a low disk loading helicopter versus the high disk loading or fan-lift V/STOL. The translational motions are also important, particularly in hover. These motions (displacements from a desired landing spot) are, at best, neutrally stable; there is no inherent tendency to return to the desired landing spot in the absence of pilot intervention. Since these motions are often controlled by attitude, the responses of which often exhibit deficient stability, it can be appreciated that precision hover is a very demanding task — particularly in gusty conditions or in the presence of destabilizing ground effects (e.g., suckdown or loss of lift close to the ground).

In summary, past V/STOL aircraft designs have exhibited one or more deficiencies in stability, controllability, and sensitivity to disturbances, particularly when judged in a context of a demanding piloting task such as a decelerating, descending precision instrument approach and landing, perhaps on the moving deck of a ship. Under such circumstances, "squirreliness" in the responses, requirements for precise coordination of a number of manipulator deflections, or excessive responsiveness to factors in the external environment severely compromise the pilot's ability to carry out his flying tasks.

FUTURE TRENDS

The technology outlined thus far is typical of V/STOL aircraft flying today, built in the late 50s to late 60s and designed even earlier. Even the recent XV-15 Tilt Rotor Research Aircraft (Figure 1a), while more sophisticated aerodynamically, employs flight control system technology of this vintage. Future V/STOLs will see a number of changes, particularly in their flight control aspects. These changes will come about as a union between the perceived need for certain kinds of improvements noted in the preceding section and the availability of the technology for realizing them outlined below.

The aircraft shown in Figure 12 represents a conceptual design of a Navy V/STOL intended for anti-submarine warfare (ASW). The long wings reflect a desire for a long flight duration capability at relatively slow wing-borne speeds — a requirement for such a mission. Beyond this, the aircraft has a superficial resemblance to a marriage between highly efficient, high-bypass-ratio turbofan engines (the large engine nacelles) and the design layout of the XV-5A (Figure 2c) with its forward fan. In actuality, the propulsion is more complex — all three fans are shaft driven and have variable pitch blades like propellers. There are two core engines in each nacelle — primarily to meet a proposed engine-out requirement (an engine can be lost in hover without catastrophic results).

FLIGHT CONTROLS

Not evident from the three-view drawing of Figure 12 is the technology to be used for control of the aircraft; indeed, decisions are still being made in this area. However, requirements for all-weather operation and for recovery (landing) aboard ships smaller than aircraft carriers both dictate higher levels of control and stability augmentation than in the past designs.

Under consideration is so-called fly-by-wire (FBW) technology, the words alluding to the fact that the hydraulic control surface positioning actuators are electrically, rather than mechanically, controlled. This approach has only recently become feasible for the primary flight controls by virtue of competitive size, weight, electrical power requirements, high reliability (through extensive redundancy with self monitoring electronics), and the inherent flexibility allowed the designer in tailoring the design for a wide range of operating conditions through full-time augmentation. Most crucial of all, FBW has won pilot acceptance, fostering a reasonably secure feeling even though there is no mechanical connection between the stick and the control surfaces. Fly-by-wire feasibility has achieved acceptance primarily because of improved

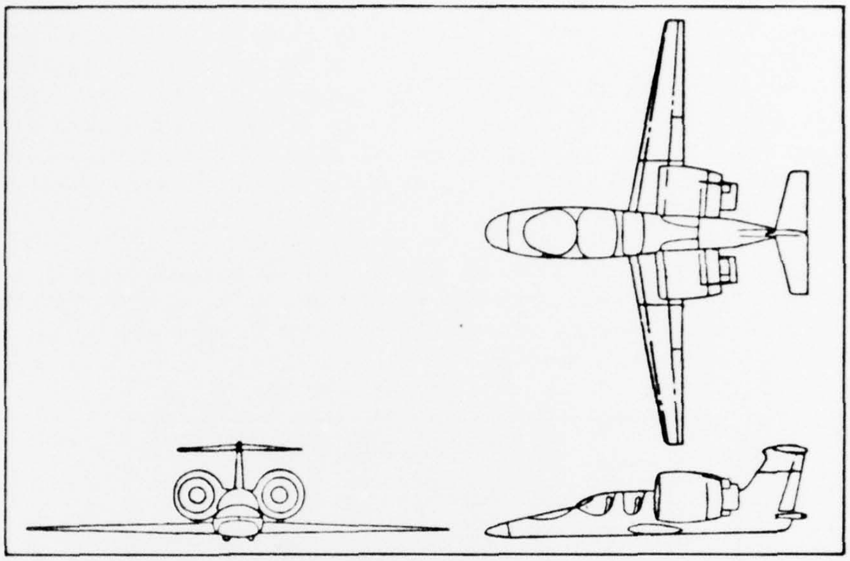

FIGURE 12. Advanced V/STOL Aircraft for ASW Operations.[7] The large engine nacelles rotate to the vertical for conversion; the nose fan is just forward of the cockpit.

electronic technology and the formidable design problems it solves in providing a viable, non-mechanical, backup control, particularly for inherently poorly damped or unstable V/STOL aircraft.

The fly-by-wire systems are generally mechanized using digital techniques, again because of the inherent flexibility. Further, the central processors in such designs can perform a variety of functions in addition to flight control. These include navigation and guidance, stores and fuel management, and providing the driving signals for a variety of electronic panel or head-up displays. Unlike typical past practice, the display system becomes electronically integrated with the flight controls and uses the same sources of sensed information.

Also under consideration are basic alternatives in form and function of the major cockpit controls. Replacing the familiar centerstick with a sidestick controller is one possibility. Another, and more fundamental, change relates to the throttle and conversion controls for transition

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[7] Adapted from S. C. Jensen and R. J. Pera. "Airplane/Engine Optimization for an Operations Lift/Cruise V/STOL Airplane," in *A Collection of Technical Papers; Proceedings of the AIAA/NASA V/STOL Conference, Palo Alto, Calif., 6-8 June 1977*. Pp. 31-39. (AIAA Paper 77-572.)

and hovering flight. It must be recognized that propulsion system control in a V/STOL is an integral part of the flight control task because of the direct and immediate effect which changes in the thrust magnitude and direction have on the aircraft motions. This carries with it strong implications with regard to the design of the pilot's displays and controls; both will tend to integrate functions which in a conventional aircraft are handled separately.

Recent simulator studies[8] have shown favorable results with a conversion control and stabilization scheme designed to overcome past V/STOL piloting difficulties during precision instrument approach cited earlier. This scheme is shown in Figure 13.

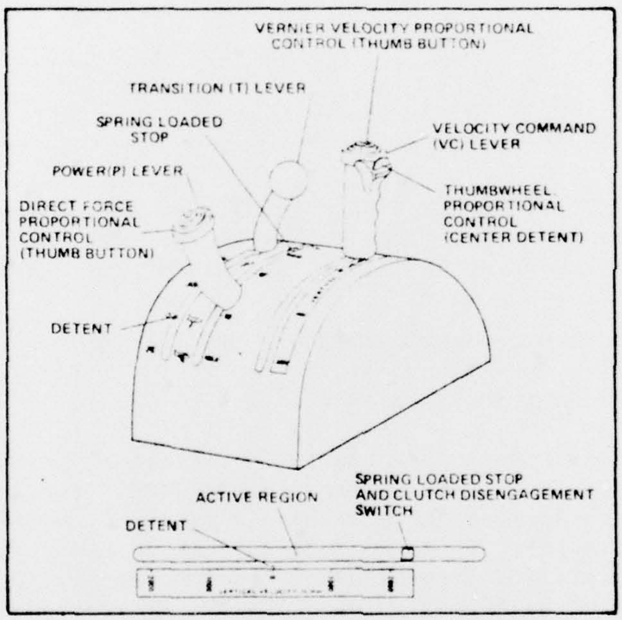

FIGURE 13. Proposed Throttle, Conversion, and Path Controls.[8] The transition lever controls thrust angle, the power lever controls thrust magnitude. Both controls function similarly to those shown in Figure 11, but the two thumb buttons and the velocity control lever are new (see text).

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8 Vernon K. Merrick and Ronald M. Gerdes. "Design and Evaluation of an Independent Flight Control System Concept for Manual IFR V/STOL Operations," in *A Collection of Technical Papers; Proceedings of the AIAA/NASA V/STOL Conference, Palo Alto, Calif., 6-8 June 1977*. Pp. 229-237. (AIAA Paper 77-601.)

Two of the Figure 13 controls, the P lever and the T lever, function like the AV-8A throttle and nozzle angle levers (Figure 11); the first controls thrust magnitude and the second controls fore-and-aft thrust angle. The thumb button on top of the throttle allows for vernier thrust (nozzle) angle control in hover, both fore and aft and laterally. Aircraft pitch and roll attitude, and heading (yaw angle) are held fixed by an autopilot.

The third control, the VC lever, automates the first two. It is used to command velocity feedback control systems in the horizontal and vertical directions. This requires velocity signals such as available from a guidance or navigation system. Deflections of the VC lever, fore and aft, command vertical velocity in transition and hover. The thumbwheel commands fore-and-aft acceleration and deceleration for transition and hover, while the thumb button on top of the lever commands horizontal vernier velocity changes in any of the four (forward, aft, left, right) directions. The primary controls, the P and T levers, move in response to the velocity feedback controls, i.e., they are driven by parallel servos. The pilot is thereby appraised of the control power he is using.

It is probably fair to state that this experimental scheme would be regarded by many in the aerospace field as a case of "overkill," i.e., it goes too far in automating the aircraft. Certainly, it is crucially dependent upon sensors capable of measuring aircraft velocities in three directions; without these signals, the VC lever is useless. On the other hand, this "radical" approach is potentially capable of curing certain of the deficiencies in V/STOL flight control which heretofore have proven intractable. Future design of the conversion controls will likely take the form of some compromise between an unaugmented configuration, typified by Figure 11, and a highly augmented configuration such as that of Figure 13.

DISPLAYS

This report has only briefly touched upon the pilot's instrument panel in connection with the need to monitor the status of engine operation, automatic flight control system, etc. The major panel instruments, e.g., attitude ball, altimeter, compass, etc., have undergone relatively little change over several decades for either conventional or V/STOL aircraft. These instruments are used by the pilot to monitor the progress of his flight and the "health" of his aircraft, much as an automobile driver watches his speed (albeit for different motivations!), and perhaps a generator charge/discharge indication, coolant temperature, etc.

But, the complexity of the equipment carried by the aircraft to perform its mission, plus the complexity of the systems used in flying the aircraft, have resulted in a proliferation of instruments, as any glance at the panel in the cockpit of an airliner will verify. Most of these are electromechanical in nature, have a single specialized function, and, when not being used in a particular phase of flight, take up panel space. The pilot finds it difficult to assimilate the information he must have to fly the airplane and carry out his mission.

Again, electronic and electro-optical technology advances have provided an answer, at least in principle. The trend in most new aircraft designs, not just V/STOLs, is for the display of information on small cathode ray tubes (CRTs) — basically special-purpose, highly sophisticated television screens called electronic multifunction displays (MFDs). Information can be displayed in a variety of abstract forms, typically limited only by the imagination of the designer and pilot acceptability. These displays operate in a variety of modes, selected via pushbutton. Thus, the pilot can "call up" a given display based upon his immediate information needs. In this fashion, valuable panel "real estate" is more efficiently used than with single function, electromechanical dial instruments.

A major variation on the MFD, which has found earlier acceptance, is the head-up display (HUD). With this device, the image is projected on a flat semi-reflective piece of glass in the pilot's forward field of view. Information is superimposed on the pilot's view of the outside world; he does not have to look inside the cockpit for critical information elements. One can view these devices as sophisticated gunsights; the major motivation for the HUD is the display of critical flight information while tracking a target at the same time. Given the presence of the HUD, one can use it in all flight phases, not just target tracking. In particular, one can be aware of one's flight status while groping (visually) for sight of the landing pad during instrument approach.

CONCLUDING REMARKS

This report has outlined certain basic aspects of V/STOL technology and the hardware and briefly discussed certain deficiencies in past aircraft which adversely impact the pilot. Many of these deficiencies are inherent in the aircraft's aerodynamics and propulsion, particularly as the disk loading (and associated top speed capability) goes up.

This does not mean that such aircraft are impractical; it does mean that a relatively greater reliance must be placed on automated features in the aircraft's flight controls than has heretofore been the case. These features will likely be as important to future V/STOL aircraft integrity as the propulsion system and the aircraft structure. The resulting V/STOL will exhibit response characteristics considerably more in tune with the pilot's capabilities and the flying tasks he must perform.

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